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RELAP-7: Progress and Future of INL's Next Generation Nuclear Power Plant System/Safety Analysis Capability (and much more)

International RELAP5 Users Group Meeting
Idaho Falls, Idaho, May 3, 2018

Richard C. Martineau, Ph.D., Director of NS&T Modeling and Simulation

Brief Overview of RELAP-7

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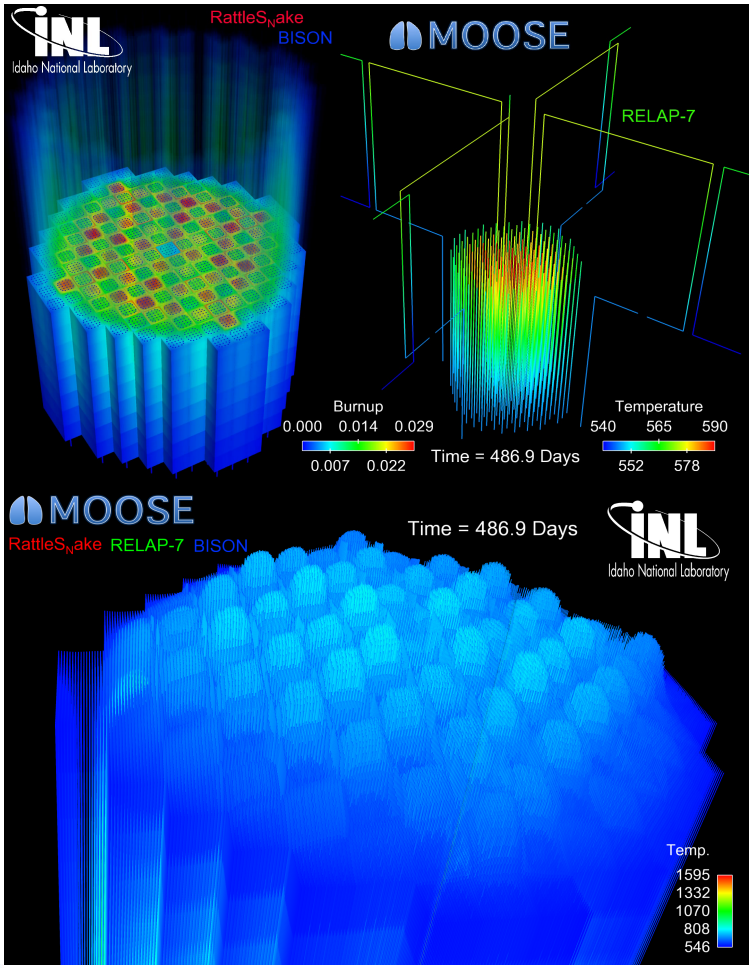
RELAP (Reactor Excursion and Leak Analysis Program)



- RELAP-7 is the next generation nuclear systems safety analysis code being developed at the Idaho National Laboratory (INL). The most important development goals of RELAP-7 are to take advantage of the previous thirty years of advancements in computer architecture, software design, numerical methods, and physical models
- First lines of code were committed to the repository on 11/07/2011. Proof of concept result, TMI-1 single phase, 06/13/2012.
- Spun off single-phase liquid version in FY 2013 for advanced SFR efforts.
- Funding Source: NEAMS
- Collaborators:

Argonne NATIONAL LABORATORY

TEXAS A&M UNIVERSITY

Massachusetts Institute of Technology

Idaho National Laboratory

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Los Alamos NATIONAL LABORATORY EST. 1943

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RELAP-7 Design Concept

The overall design goal of RELAP-7 development is to leverage 30 years of advancements in software design, numerical integration methods, and physical models.

- **Modern Software Design:** ***What MOOSE brings to the table.***
  - Object-oriented C++ construction (www.mooseframework.org)
  - Designed to be easily extended (modular physics) and maintained
  - Strict adherence to SQA (meeting NQA-1 requirements)
- **Advanced Numerical Integration Methods:**
  - Multi-scale time integration, PCICE (in progress), JFNK (implicit nonlinear Newton method), and a point implicit method. Second-order accurate spatial discretization (linear finite elements or reconstructed Discontinuous Galerkin).

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RELAP-7 Design Concept

- **State-of-the-Art Physical Models:**
  - All-speed, all-fluid (vapor-liquid, gas, liquid metal) flow – agnostic of reactor concept (PWR, BWR, SMR, SFR, LFR, MSR, FHR, HTGR, etc.).
  - 7-equation two-phase, two-pressure flow model incorporating IAPWS-95 equation of state.
  - New two-dimensional core heat transfer model based upon fuel, gap, clad.
  - Closure relations from the TRACE V5.0 code.
  - Designed for multiphysics analysis (BISON, Marmot, MAMMOTH, Rattlesnake) or to couple to multi-D core simulators (CASL's VERA or NEAMS Pronghorn) with MOOSE MultiApp and Transfers.

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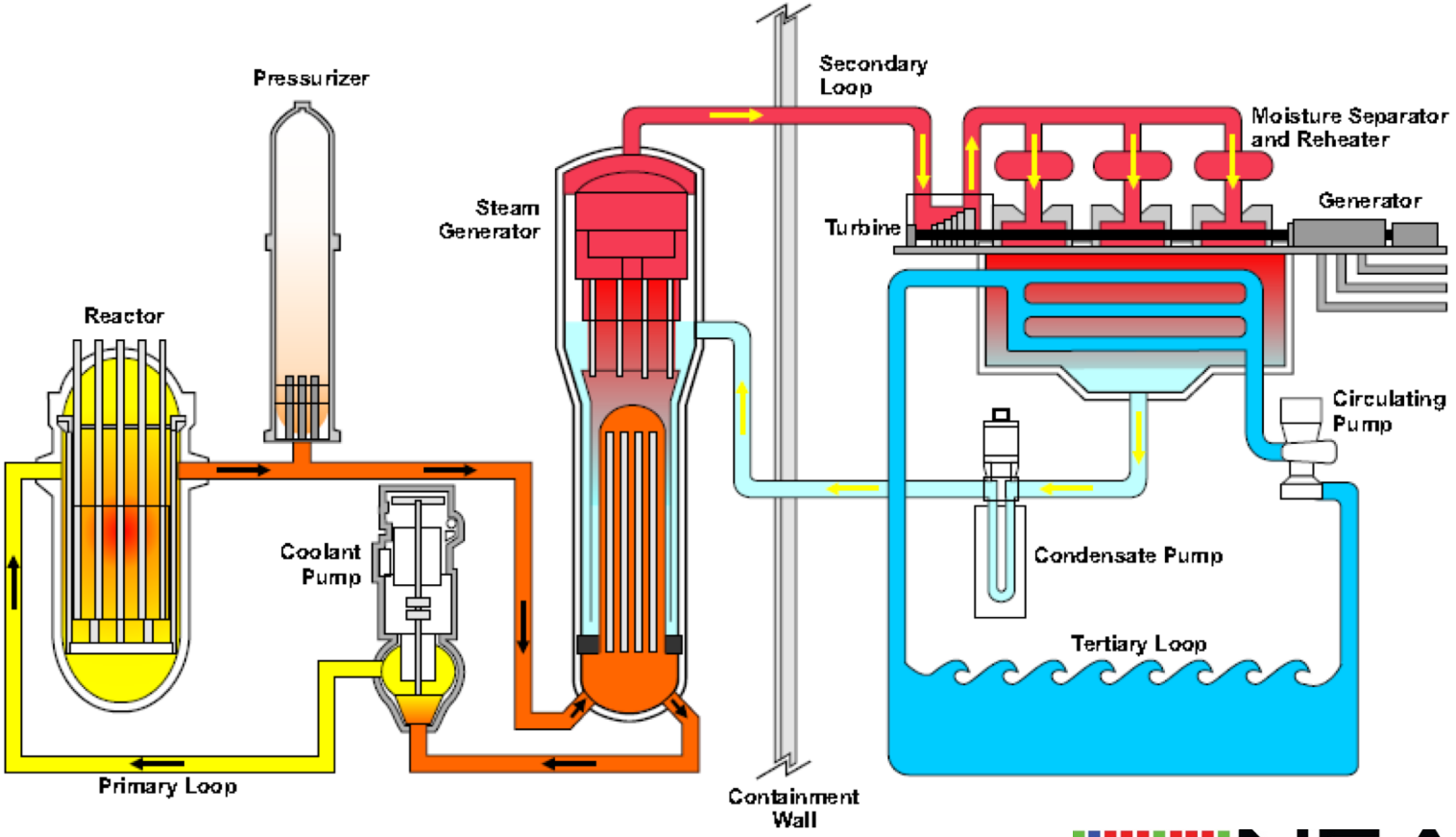
Typical Nuclear Power Plant Systems Analysis (RELAP5, RELAP-7, TRACE, RETRAN, Etc.)

System describe by 0D and 1D Components



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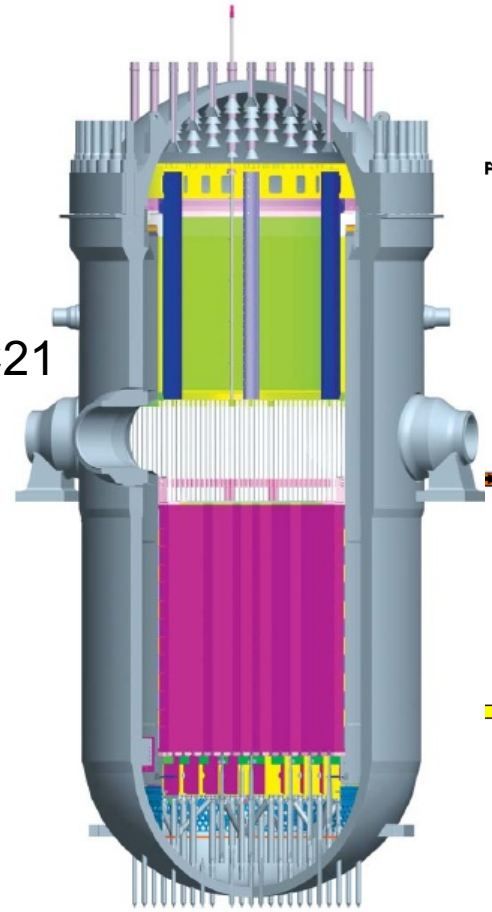
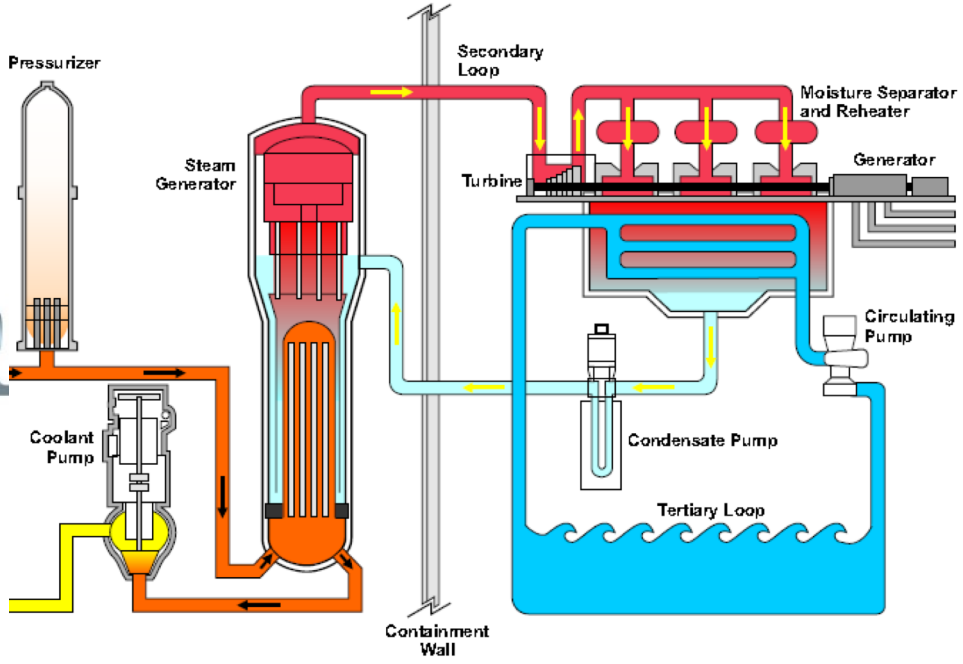
In the Future, Multi-scale, Multi-dimensional Multi-physics, Nuclear Power Plant Systems Analysis

MAMMOTH-
Rattlesnake
MCNP/Serpent/MC21
CFD informed
MAMBA
Hognose
BISON/Marmot
Grizzly (RPV CIs)
RELAP-7 (3D SC)
Pronghorn



RELAP-7 (Balance of Plant)



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Recent Developments in RELAP-7

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FY-2018 RELAP-7 Milestones

1. **M1MS-18IN0301124 -** Complete report documenting RELAP-7 Theory Manual and User's Manual update, due March 31, 2018.
2. **M2MS-18IN0301122 -** Complete report on RELAP-7 verification results of the TRACE 5.0 CRs for post-CHF (critical heat flux) conditions, due June 30, 2018.
3. **M2MS-18IN0301128 -** Complete report on development and implementation on non-condensable gas phase capability in RELAP-7, due August 31, 2018.
4. **M2MS-18IN0301126 -** Complete report documenting Verification and Validation of Water Properties for RELAP-7, due September 28, 2018.
5. **M3MS-18IN03011210 -** Complete report on preliminary Multi-SERTTA TREAT experiment with RELAP-7, due September 28, 2018.

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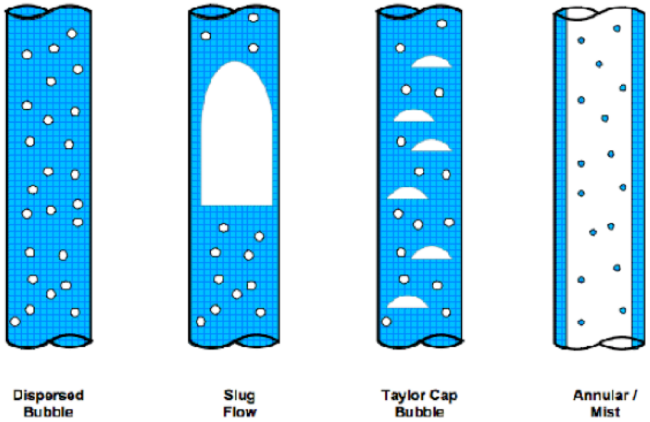
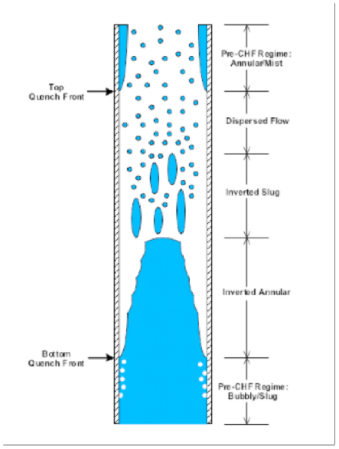
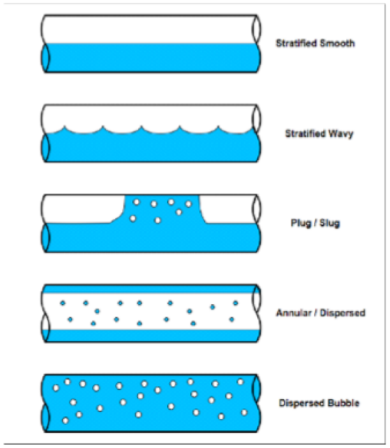
Complete Implementation and Testing of TRACE 5.0 Closure Relations



Vertical pipes, pre-CHF



Vertical pipes, post-CHF



Horizontal pipes, pre-CHF

- R.C. Johns, G.B. Swindlehurst, D. Andrs, R.A.Berry, J.E. Hansel, R.C. Martineau, L. Zou, ***Closure Verification Part 1: Vertical PreCHF Closures,*** LA-UR-17-28769, 2017.
- Milestone Completion on June 30, 2018.

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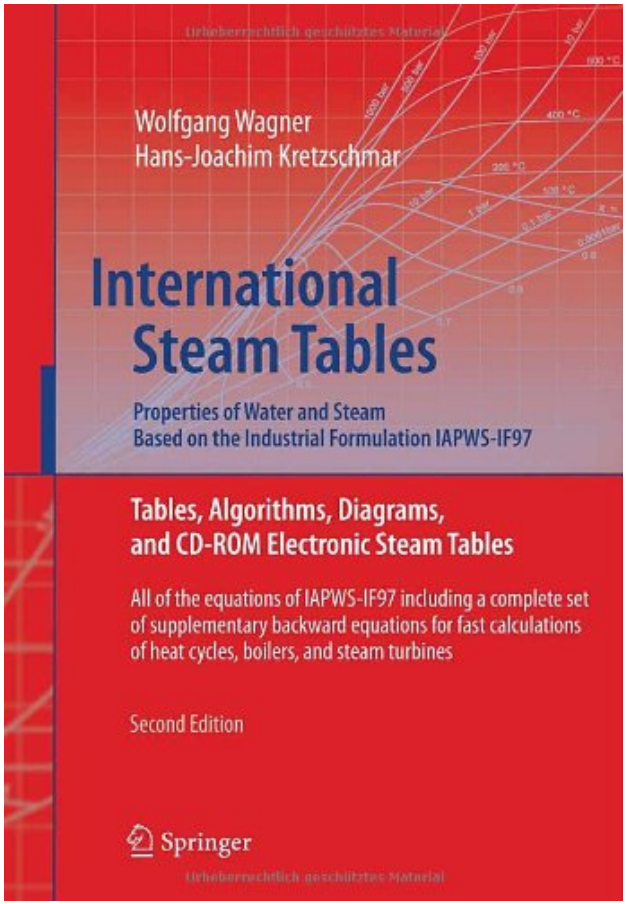
RELAP-7 Water/Steam EOS V&V and Non-Condensable Gasses

- V&V of International Association for Properties of Water and Steam, IAPWS-95 steam/water properties package developed for MOOSE (Milestone # 4 September 30, 2018)
- Helium and Nitrogen equation of state packages implemented under MOOSE (Milestone #3 August 31, 2018)
- Mass fraction transport equations currently being implemented in RELAP-7 (Milestone #3 August 31, 2018)



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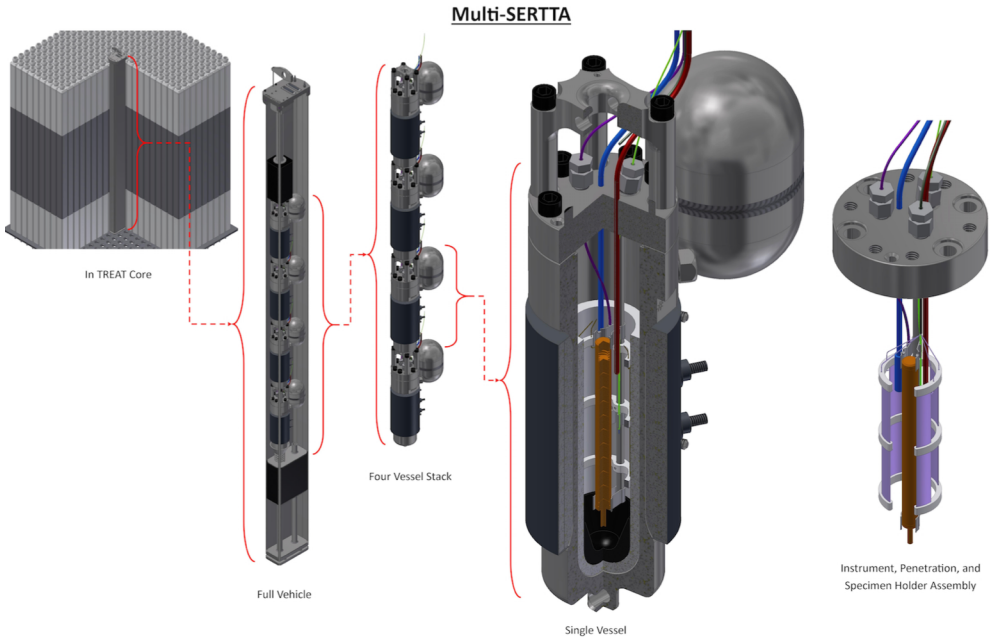
RELAP-7 Water/Steam EOS V&V and Non-Condensable Gasses

- **The TREAT multi-SERTTA modeling and simulation effort seeks to assist in the design of fuel experiments, and eventually use experimental data to improve fuel modeling.**
- **We will demonstrate an initial capability of RELAP-7 two-phase water/Nitrogen tightly coupled to the BISON nuclear fuels performance. (Milestone #5 September 30, 2018)**



The multi-SERTTA irradiation vehicle is designed to enable transient testing (TREAT) of PWR type fuel specimens, including fuel concepts with enhanced accident tolerance (Accident Tolerant Fuels, ATF), as well as other types of compatible specimens.

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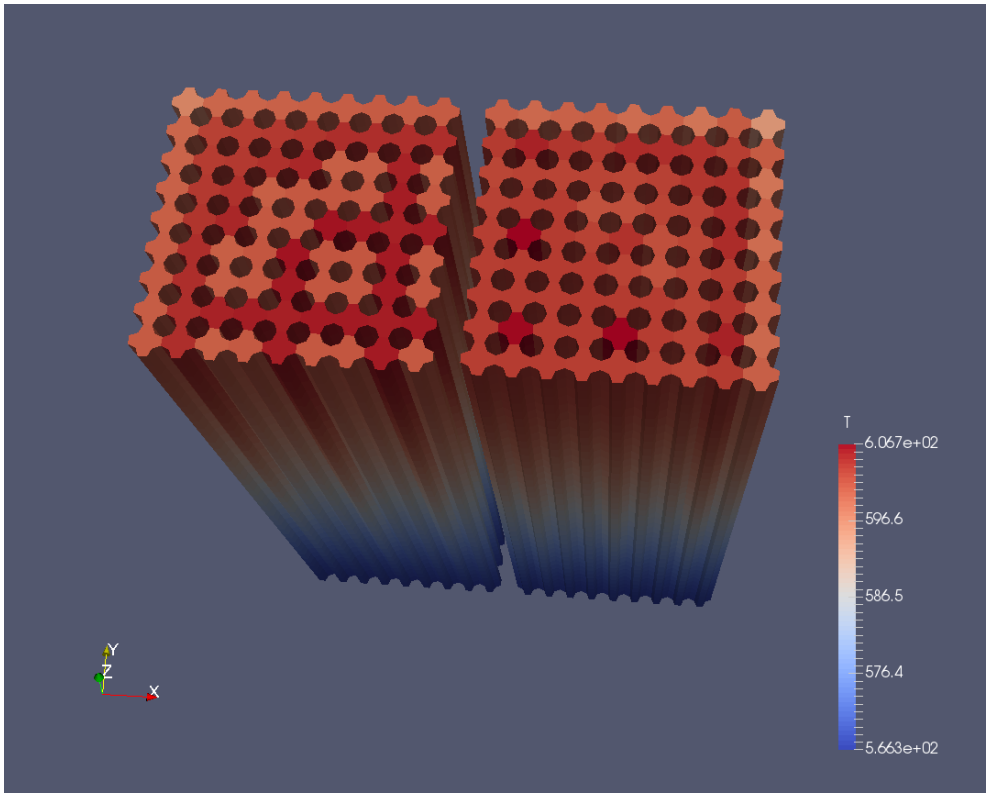
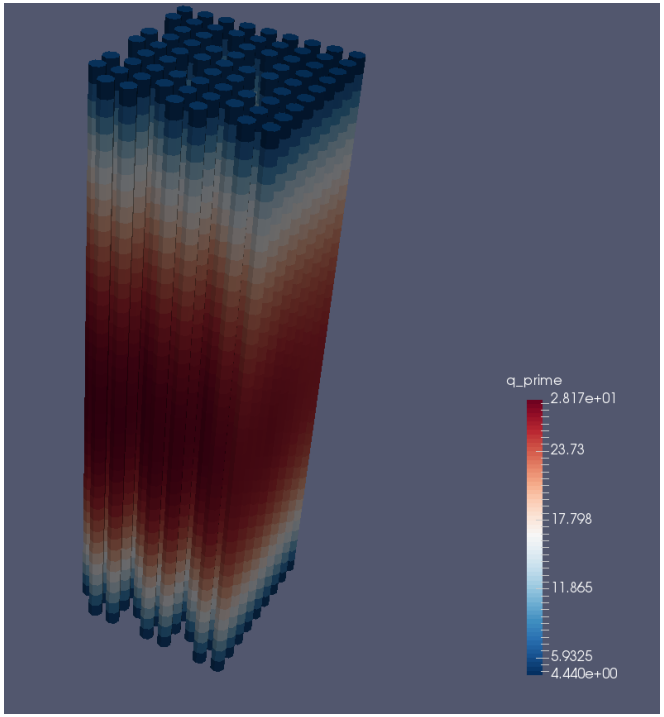
Progress on development of 3D Subchannel Flow

Development of Native RELAP-7 3D Subchannel Flow Capability:

- Initial single-phase development at MIT, Kord Smith, Ben Forget, and Sterling Harper. Improved CASMO/SIMULATE (Studsvik) approach.





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RELAP-7 Developments in the near Future

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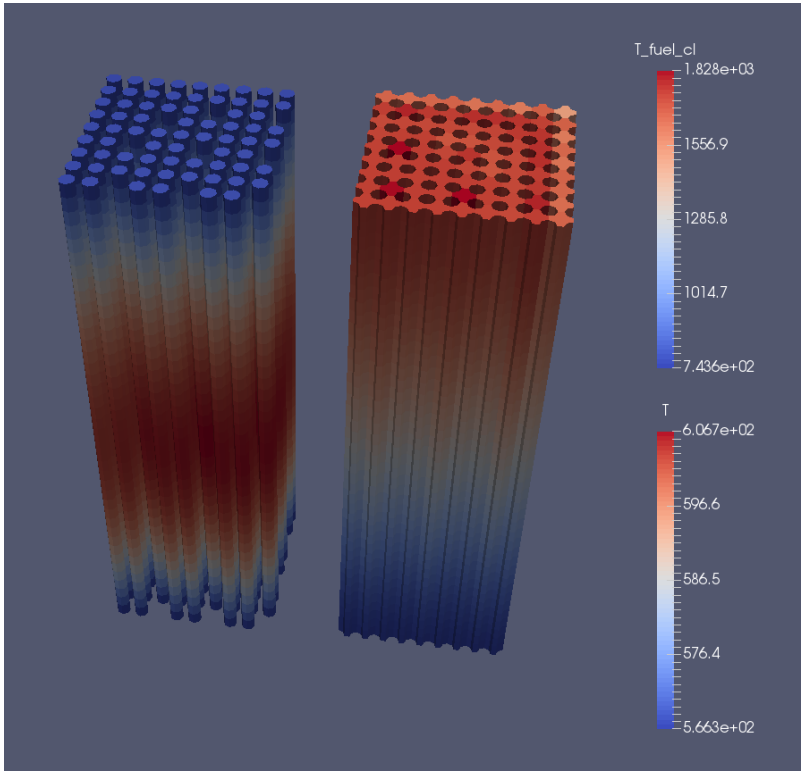
Future Developments of Single and Two-Phase 3D Subchannel Flow in RELAP-7

- Closure relations for assemblies.
- Validation at TAMU.
- Development of 7-equation two-phase 3D subchannel (TAMU PhD student).
- Both 3D subchannel formulations tightly coupled to BISON. No traditional pin heating models.
- BISON/RELAP-7allows realistic fuels performance to be included in core calculations.
- MOOSE implicit calculation with MAMMOTH/Rattlesnake allow for detailed core burnup over life of fuel.



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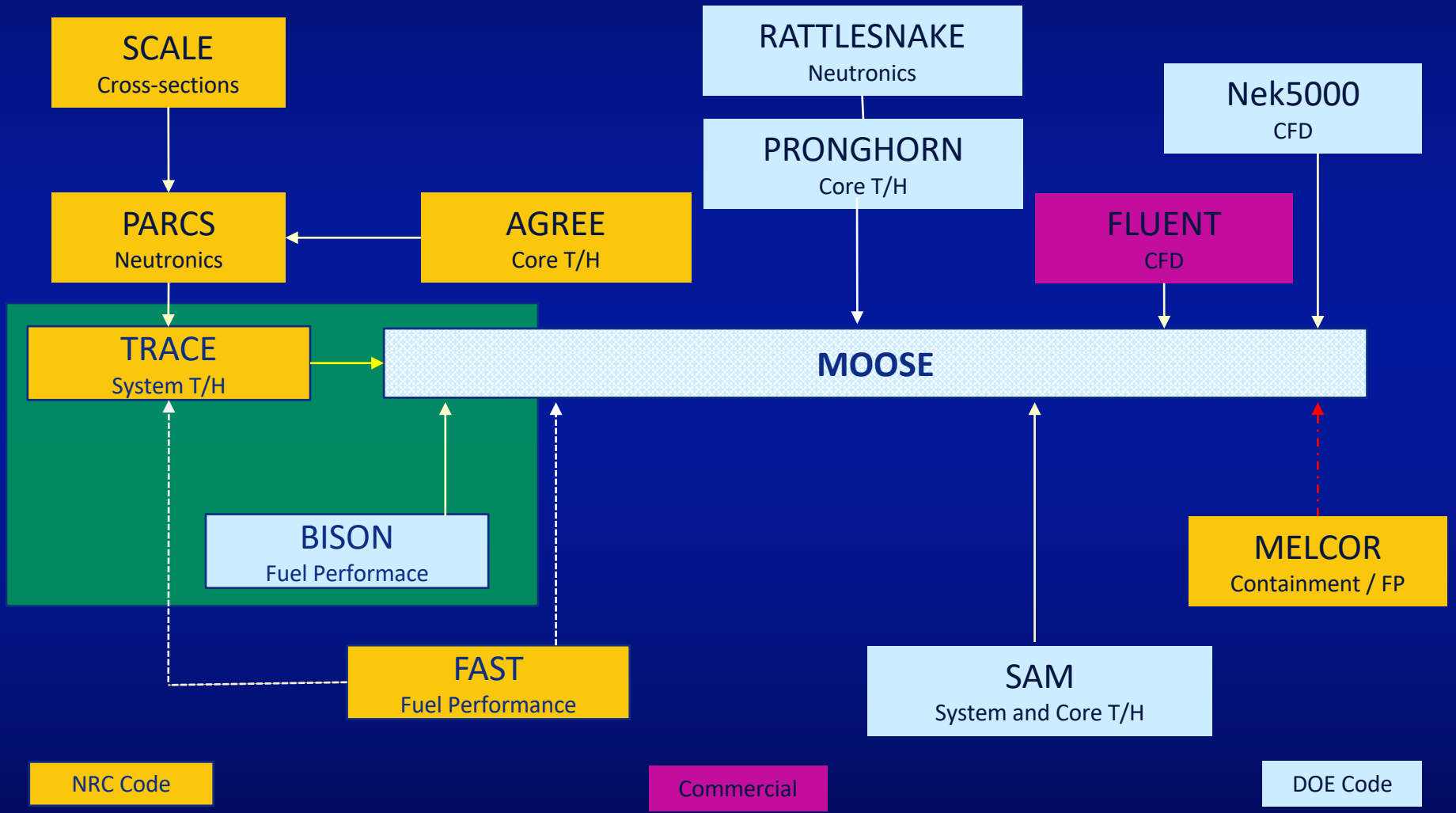
The Future: Major RELAP-7 Capability Development Tasks

- Improved LWR components (1D-2D downcomer, 1D pressurizer, various steam generator designs) to provide improved water level tracking and LOCA temporal accuracy.
- Tightly coupled multiphysics fuels performance and reactor physics (NEAMS and CASL core simulator applications) for improved design and safety analysis.
- Complete development and implementation of two-phase compressible branch for pipe network.
- Conduct experiment designed to measure two-pressure field for 7-equation pressure relaxation term.
- Oxide species transport models for CRUD and Boron deposition analysis in CASL (MAMBA and Vulture).

TRACE-BISON Coupling

NRC's Blue CRAB (Comprehensive Reactor Analysis Bundle) MOOSE-based approach



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Blue CRAB, NRC's Advanced Reactor M&S Application (Cont.)

- **Multiphysics Software Objectives:**
  - To perform coupled thermo-hydraulics/nuclear fuels performance analysis Accident Tolerant Fuels (ATF) concepts, including:
    - FeCrAl Cladding
    - U_3Si_2 Fuel
    - Cr_2O_3 Doped Fuel
    - Light Bridge Fuel
    - Oklo, Inc. Hexagonal Fuel
  - To analyze LWR ATF concepts for normal reactor operation up to Large Break LOCA events, normal operation, blowdown phase, refill phase, and reflood phase.
  - To analyze Advanced Reactor Concepts (ARC).

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Blue CRAB, NRC's Advanced Reactor M&S Application (Cont.)

Progress to Date:

- Blue CRAB stand up occurred on 09/21/2017.
- Under Blue CRAB, TRACE and BISON are now compiled under one executable capable of interleaved execution and information exchange.
- Blue CRAB can spawn single or multiple instances of TRACE (good for probabilistic analysis, PRA).
- BISON and TRACE are now coupled through continuous heat flux with BISON 2D *r-z* axisymmetric heat structure.

Future Work:

- Integrate TRACE 1.5 D heat structure with BISON 1.5D heat structure.
- Implement MOOSE adaptive mesh consistent with TRACE for LOCA events.
- Incorporate cladding displacements from BISON.
- Extend TRACE data interface to allow communication with more MOOSE Apps

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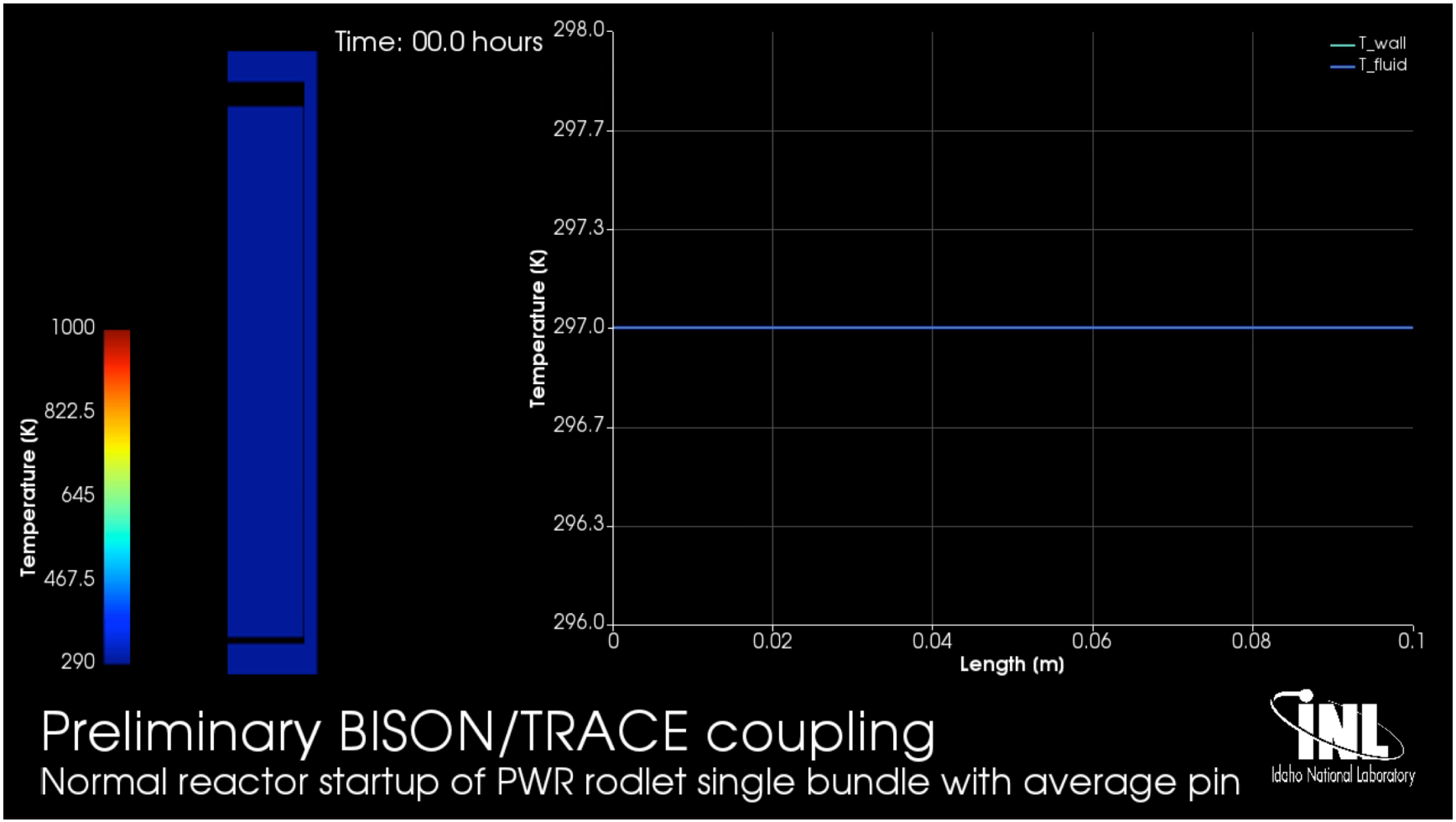
12 hour Power up Transient for 10cm Rodlet using TRACE-BISON (Blue CRAB)



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Integration of RELAP5 and RELAP-7 Efforts

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10-Year Plan for Integration of RELAP5-3D and RELAP-7 Efforts

Purpose: ***To extend the life and capability of RELAP5 for as long as necessary to support industry and the US Navy. Efforts will require an additional $1.7M/year for both RELAP5 and RELAP-7***

- RELAP5 capability needs to be extended to address current issues, such as with various LOCA events and hypothetical fuel failure scenarios. Thus, we will leverage the the NRC TRACE-BISON coupling effort that we are currently developing and modify the Blue CRAB MOOSE MultiApp to tightly couple RELAP5-3D to BISON. BISON could be deployed (with the proper licenses) as a submodule option to be installed and compiled with RELAP5. Extensive re-validation efforts for RELAP5 will be initiated as RELAP5 will now include significant fuels performance physics. These validation cases will also be available to RELAP-7 V&V.

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10-Year Plan for Integration of RELAP5-3D and RELAP-7 Efforts

- RELAP5 continues to carry the load for civilian and NR efforts. However, RELAP5-BISON analysis tasks will include addressing NRC 50.46c, which introduces new more restrictive performance-based requirements. This rule may require re-analysis of all existing U.S. LOCA basis for current fuels. Furthermore, Accident Tolerant Fuel (ATF) concepts can then be evaluated for various LOCA events and estimating coping times with a coupled RELAP5-BISON capability.
- Near Term Benefits:
  1. Industry will have RELAP5-3D with the same advanced multiscale fuels performance that the NRCs Blue CRAB with TRACE-BISON.
  2. The NRC can maintain its regulatory independent analysis capability using the TRACE code as the systems codes will be different. Thus, separate validation of RELAP5-3D/BISON will be compared with a validated TRACE/BISON capability.
  3. Industry will be in a better position to address new regulatory requirements.
  4. The NRC and Industry will have better tools to evaluate and design ATF concepts.
  5. RELAP5-3D/BISON will be a definite improvement over standalone RELAP5-3D for many LWR analysis that require detailed fuel performance capability.

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10-Year Plan for Integration of RELAP5-3D and RELAP-7 Efforts

Key RELAP5-3D Development Efforts:

- Bison Coupling to RELAP5-3D for ATF related activities that leverage the existing Bison-TRACE coupling.
- Best Estimate Plus Uncertainty capability. The Best-Estimate Plus Uncertainty (BEPU) methodology has become the de-facto standard in the nuclear industry to perform safety analysis of NPPs.
- Improved Code Robustness.
- Improve the Nearly-Implicit Modeling for 3-D applications and modify the switching from nearly- to semi-implicit time advancement.
- Increase code speed by activities such as enhance vector and OpenMP parallel coding in the hydrodynamics and heat structures
- Improve long term code maintenance by refactoring, elimination of obsolete constructs, remove all non-ANSI conditional coding for machines and compilers that no longer exist, removal of memory leaks.
- Examine Naval Reactors Code capability currently in NUPAC for possible inclusion in RELAP5-3D.

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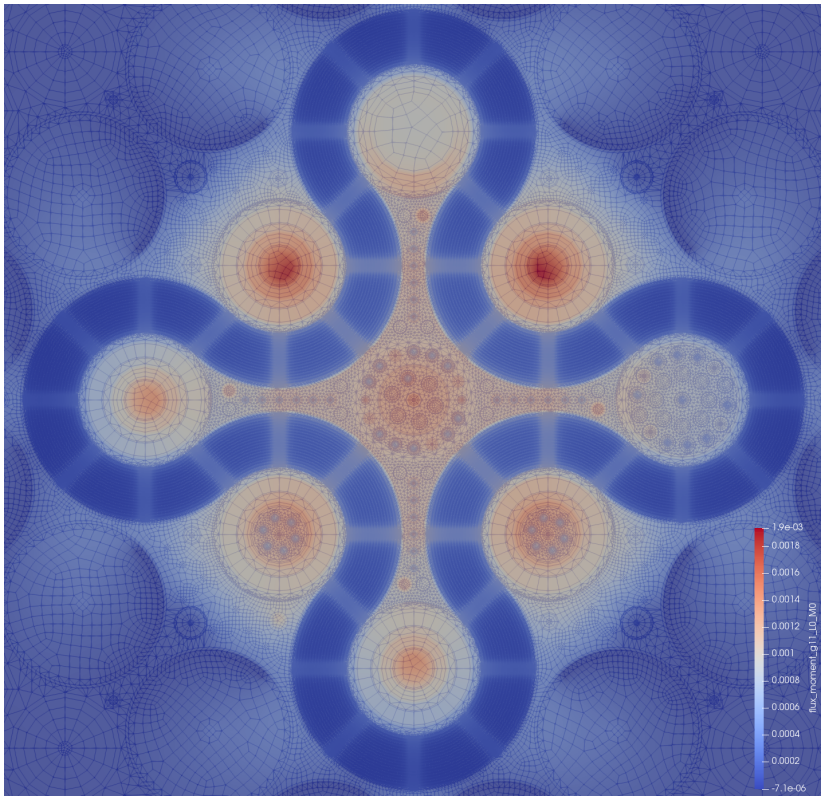
QUESTIONS?

Rattlesnake Radiation Transport Simulation of the ATR Core:

- 2D unstructured mesh with 262,983 elements (mixed element types).
- Self Adjoint Angular Flux (SAAF) formulation for transport equation.
- Cross sections are generated with SCALE.
- 12 energy groups.
- Gauss-Chebyshev angular quadrature, 256 streaming directions.
- NDOF = 786,447,360.
- 16 nodes on INL's FALCON supercomputer.
- Direct transport k-eigenvalue calculation with PJFNK.
- On right, flux in group #12.
- Wall time 7390s about 2 hours.



ATR core simulator is being developed from MOOSE coupled RELAP-7, MAMMOTH/MC21 And BISON

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